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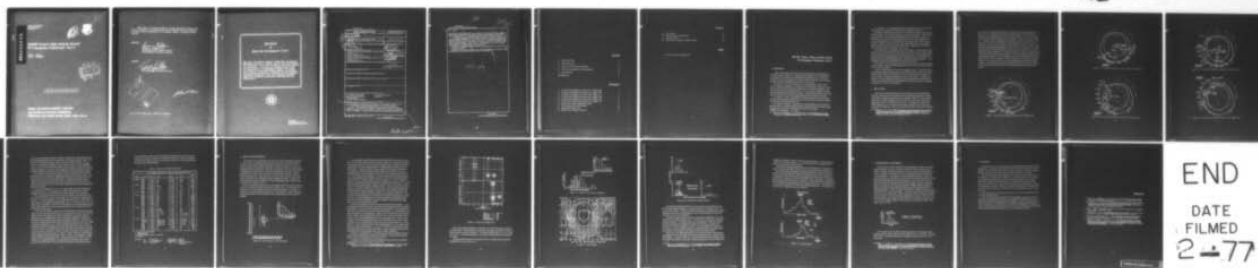
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DAASM PROJECT - HIGH LATITUDE AIRCRAFT HF PROPAGATION EXPERIMEN--ETC(U)
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RADC-TR-76-235

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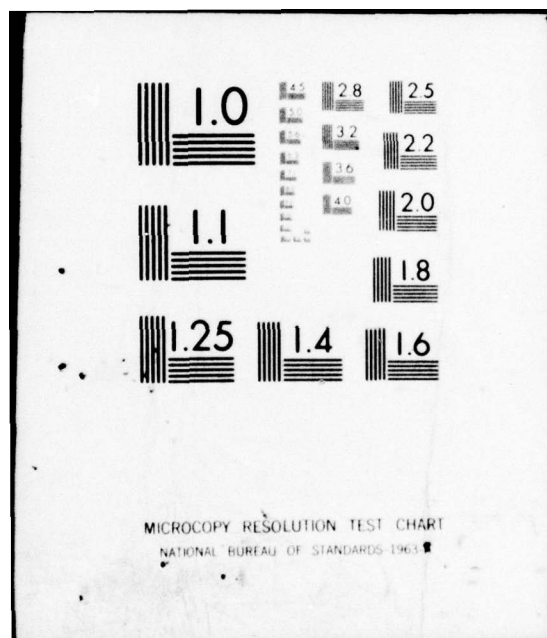
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DAASM Project—High Latitude Aircraft HF Propagation Experiment, Part II

**GARY S. SALES
JOHN I. VIDESBERG**

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The purpose of the DAASM project was to investigate the effects of the auroral ionosphere on long-range propagation of HF radio signals. The HF radio signals transmitted from an aircraft and received at Goose Bay, Labrador, were analyzed to determine the degree to which the Doppler frequency and arrival angle were perturbed by passage through the auroral ionosphere. As part of this analysis the propagation modes for each			

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data sample were determined, using vertical and oblique incidence sounders. The experiment detail and the data, analyzed in this report in more detail, were described in a prior DAASM report (AFCRL-TR-75-0290/ERP No. 516).

E-mode propagation dominated the data samples and may be considered good propagation conditions. The median value for the absolute angular deviation was 2° from the true bearing of the aircraft, well within the uncertainty of the aircraft position. The maximum deviation was 9° . The median value for the angular spreading was 4° and it varied between 2 and 6° . F-mode signals showed a median angular spreading of 5° .

Finally, the Doppler frequency spread varied between 0.3 and 0.8 Hz with a median of 0.33 Hz.

In general, the auroral effects on E-mode propagation were small, though considerably larger than would be expected at midlatitude.

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DAASM Project - High Latitude Aircraft HF Propagation Experiment, Part II

1. INTRODUCTION

A basic description of the Doppler/Arrival Angle Spectral Measurements (DAASM) project was given in a preceding report¹ together with a discussion of the original early results and a compendium of significant data. The DAASM system has operated at Goose Bay, Labrador (53°20'N, 60°20'W), for about one and one-half years beginning full operation in January 1974.

The purpose of the DAASM program was to investigate the effects of the auroral and polar ionosphere on a backscatter sounding system while at the same time receiving forward-propagated signals from an airborne transmitter. The aircraft used for these experiments was a KC-135, specially equipped for ionospheric investigations and the DAASM project. The DAASM project was concerned with the character of the received signals and focussed on three main areas:

(a) Angle of Arrival - The degree to which the signals from the aircraft is deviated from the known bearing to the aircraft and the amount of angular spreading associated with the particular path.

(b) Doppler Frequency - The extent to which propagation in the auroral regions deviates the expected Doppler frequency associated with the aircraft motion and the amount of frequency spreading that occurs on the signal.

(Received for publication July 1976)

1. Sales, G.S., Videberg, J.I., and Varad, R. (1975) DAASM Project - High Altitude HF Propagation Experiment, ERP No. 516, AFCRL-TR-75-0290.

(c) Coherence - The temporal and spatial coherence of these aircraft signals after propagation through the irregular auroral propagation medium.

The basic concept of the DAASM system is to record on digital magnetic tape the signal output of each of the antennas in a large receiving array. This recorded data represents a two-dimensional description of the received wave field; the dimensions being time and one-dimensional space across a linear antenna array. In the simplest approach, a two-dimensional Fourier transform of this data set results in a Doppler frequency/arrival angle description of the received signal. These transforms were accomplished at the AFCRL computer facility after the data tapes were returned from the Goose Bay site.

The sampled data, as explained in the earlier report,¹ is limited both in time and space because of the finite duration of the time sample (32 sec) and the limited extent of the antenna array (910 m maximum) and thus, the resulting Doppler frequency and arrival angle description of the signal is limited in resolution. This is particularly true of the spatial dimension. Advanced processing techniques were developed to improve the capability of the system in this area.

This report is aimed at relating the observed character of the received signals to the propagation mode and other geophysical factors, particularly those affected by the auroral ionosphere.

The basic approach was to identify the propagation mode or modes for each of the samples of significant data from the six aircraft missions carried out in cooperation with the Goose Bay Observatory in 1974. The data is then examined for characteristics and features associated with the various modes. In addition, an analysis is made of statistical trends and related predictable geophysical phenomena having a potential for the determination and prediction of optimum operating conditions for an OTH-B radar system.

2. MODE ANALYSIS

Information for the identification of the propagation modes was obtained by utilizing a combination of the measured vertical and oblique ionograms, together with synthetic ionograms calculated from a prediction program.² The measured ionograms are taken, at both the Goose Bay and the aircraft ends of the circuit, sequentially with the DAASM data at Goose Bay. The sequence for most of the flights consists of 1.5 min DAASM runs interlaced between 1-min vertical and 1-min oblique ionograms. Thus, the time interval between either type of ionogram

2. Barghausen, A. F. et al (1969) Predicting Long Term Operational Parameters of High Frequency Sky-Wave Telecommunications Systems, ESSA Tech. Report ERL 110-ITS-78, (Blue Deck Polar Model, Aircraft Version with Doppler Summary, AFCRL modification 1975).

is 5 min and the largest interval between a DAASM "map" and an ionogram is less than 2.5 min. Normally this interval is sufficiently small to neglect temporal changes in the ionosphere such as occur at lower latitudes. In the Arctic regions, it was frequently observed that significant changes occurred over this time interval. In some cases these changes occurred at one end of the circuit but not at the other end. Inasmuch as the critical data determining the mode occurs at the reflection points, either the mid-path for a one-hop mode, or the 1/3 path for a two-hop mode, these end-path ionograms must be utilized with discretion. By carefully considering the location of the reflection points relative to auroral oval, as indicated in the plots of Figures 1 to 6, together with the more likely modes determined with the assistance of the ITS-78 computations,² the most nearly applicable vertical ionogram is selected. These ionograms are then used, together with standard transmission curves, to construct an oblique ionogram. This constructed oblique ionogram is then used as an aid in scaling and calibrating the measured oblique ionogram. This technique is useful in the identification of the measured ionogram traces, which often includes both forward propagation signals and backscatter echoes.

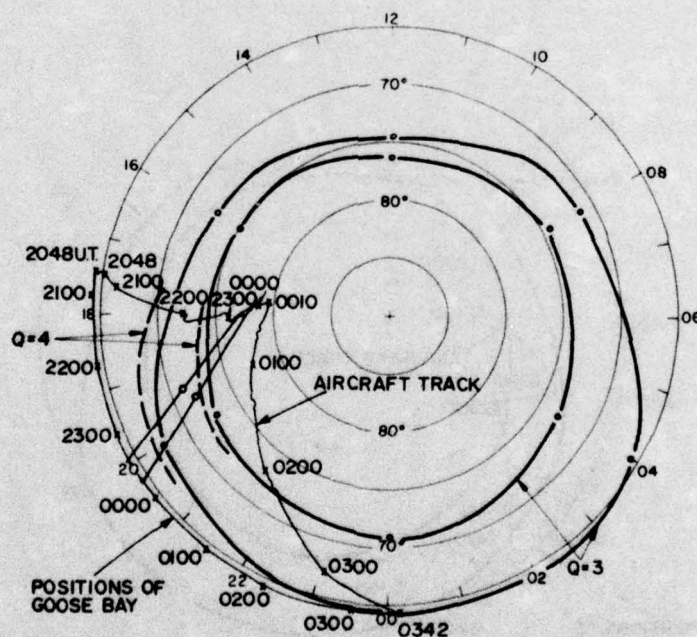


Figure 1. Aircraft Track Relative to Auroral Oval, Flight 4-058

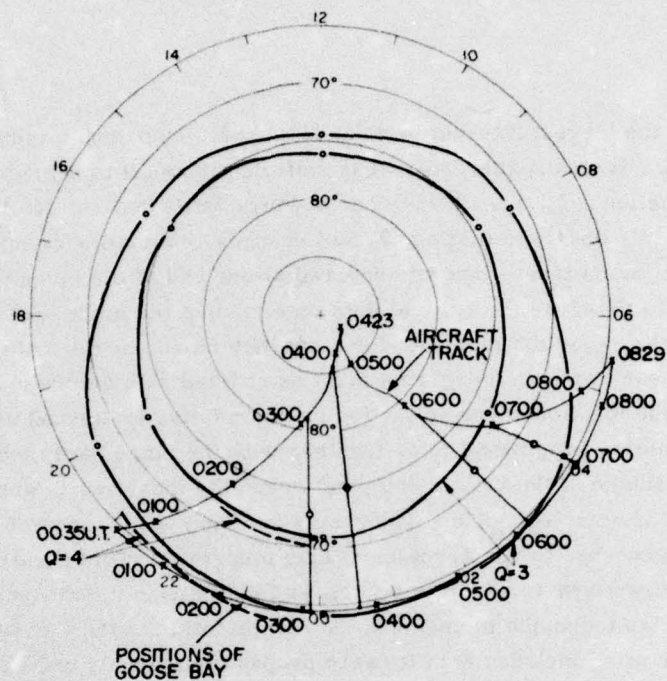


Figure 2. Aircraft Track Relative to Auroral Oval, Flight 4-060

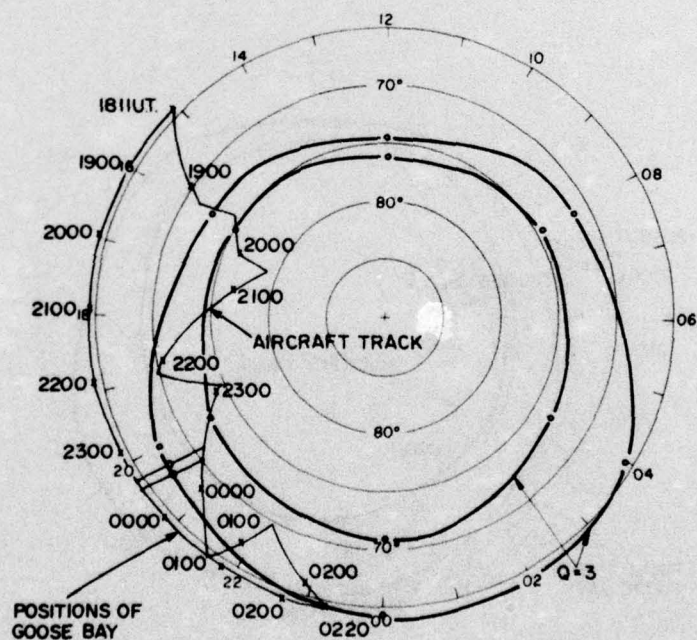


Figure 3. Aircraft Track Relative to Auroral Oval, Flight 4-141

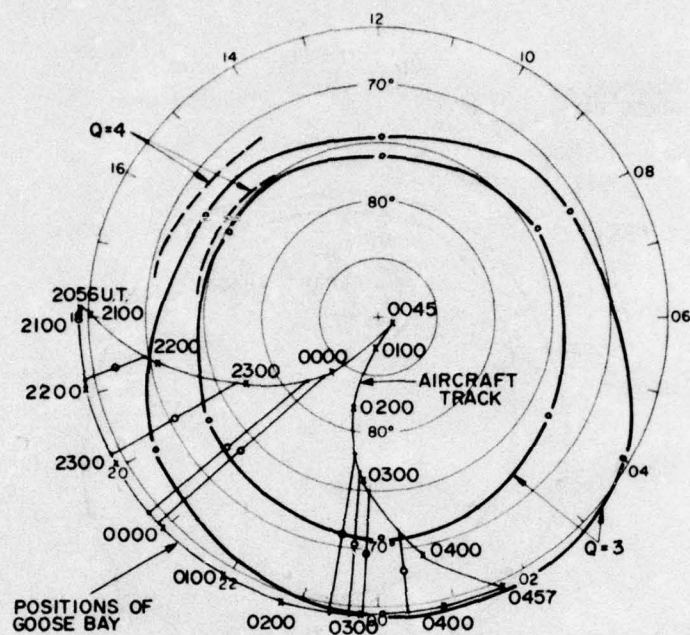


Figure 4. Aircraft Track Relative to Auroral Oval, Flight 4-142

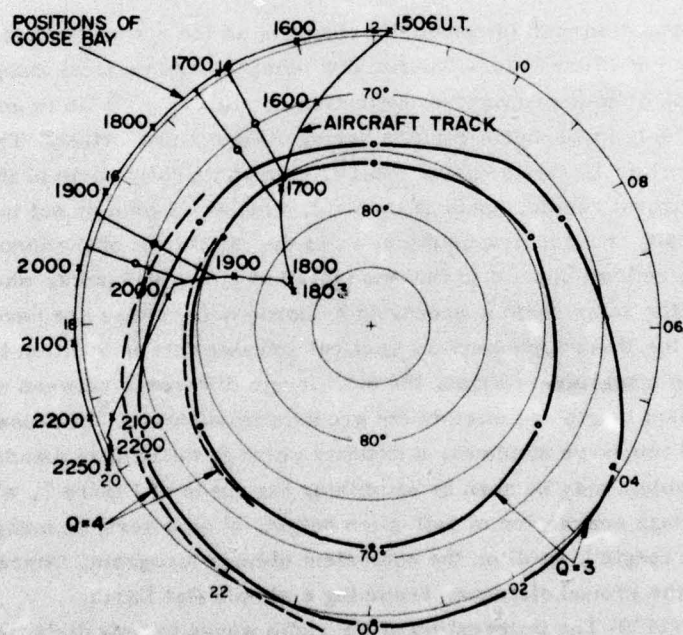


Figure 5. Aircraft Track Relative to Auroral Oval, Flight 4-193

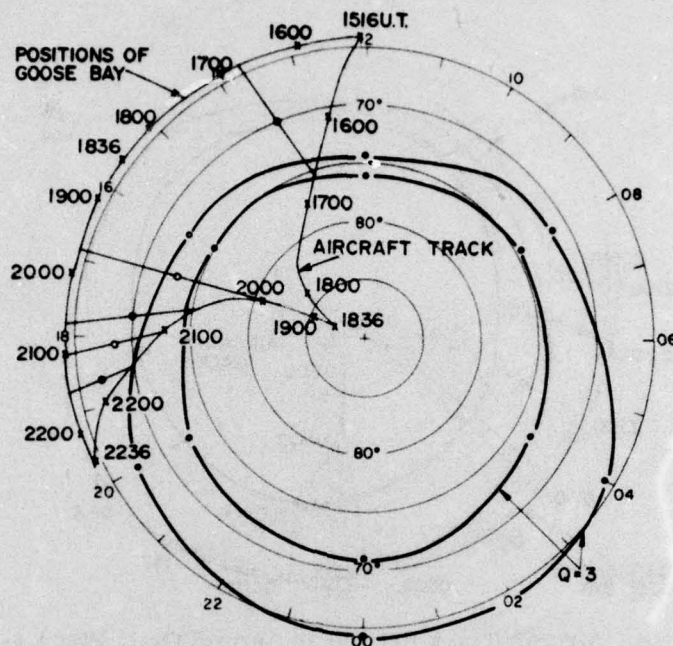


Figure 6. Aircraft Track Relative to Auroral Oval, Flight 4-196

The propagation path is constantly changing as the aircraft proceeds with an average speed of 13 km/min. The two end points where vertical ionograms are made, and the oblique propagation reflection point(s) may all lie in any one or more identifiable ionospheric regions having different properties. These are: (a) the auroral oval, (b) the polar cap region magnetically north of the oval, or (c) the subauroral region, south of the oval, which may or may not include the electron-density trough. Assumptions as to the similarity of the ionosphere at the mid-path reflection point to that measured at either end point, when both end points lie in the same region, appear to be borne out. There are several reasons for the need for this supplementary vertical sounder data in addition to the measured oblique ionograms. First, the path-length difference between modes defined as "excess path length" relative to the ground path distance,³ represents the small difference of two large numbers, a quantity which is difficult to measure accurately. This problem may be seen by examining the curve of Figure 7, which may be used for a rough conversion of reflection height, h' on a vertical ionogram, to "excess path length", $(p-d)$ on the equivalent oblique ionogram, where p is the path length, d is the ground distance, assuming a simple flat Earth.

3. Kift, F. (1960) The propagation of HF radio waves to long distances, Inst. of Elec. Engrs., Paper No. 3156E.

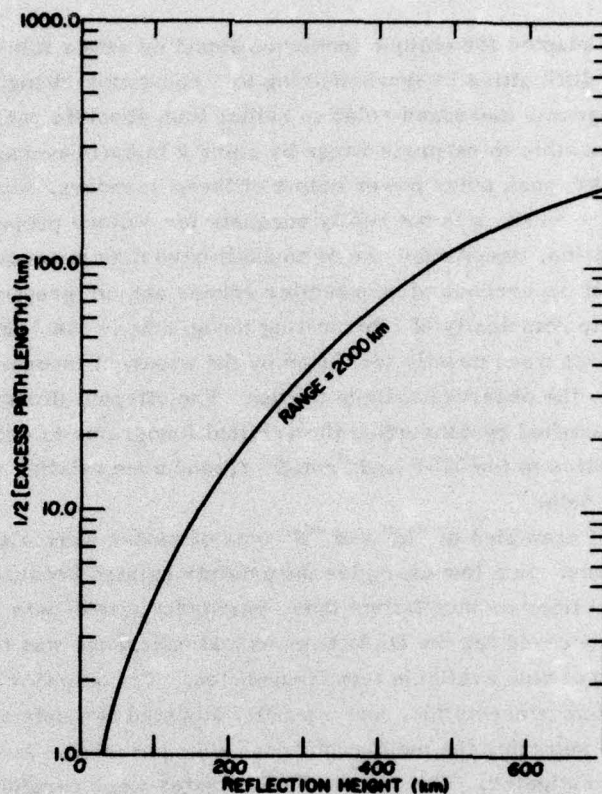


Figure 7. Excess Path Length vs Reflection Height

It may be seen that for large distances, and/or reflection from low heights, that there is great difficulty in reading path differences. For example, at 2000 km range, the "excess path lengths" corresponding to a 1E-mode at a 100 km height, and 1F₁ mode at a 200 km height are approximately 8 km and 34 km respectively. The error due to neglecting the earth's curvature for this example is negligible compared to the measurement accuracy available with even a reasonable high-resolution oblique sounder. Thus, it can be seen that a resolution of better than 26 km is required to distinguish between these two modes.

In the case of the sounding system available for the DAASM experiment, other limitations were imposed. First, the sounders used (Digisondes) were highly sophisticated in terms of their design and digital processing. However, they were essentially designed for vertical sounding, where the typical pulse resolution of 15 km is more than adequate. As illustrated in the above example, however, special short pulse techniques would be required for accurate determination of the complex mode structure usually found in high latitude oblique propagation. Second,

the system was adapted for oblique incidence sounding with a fast-moving aircraft, thus presenting difficulties in synchronizing to a constantly changing range. Thus, the oblique ionograms measured relative rather than absolute range. In some cases, it was possible to estimate range by using a bistatic averaging technique. Finally, the 10 kW peak pulse power output of these sounders, while sufficient for vertical incidence work, was not really adequate for oblique propagation in regions of higher absorption, despite the use of sophisticated data processing techniques.

The frequent occurrence of backscatter echoes and off-great-circle oblique signals add to the complexity of interpreting ionograms in the Arctic region. The backscatter echoes were usually identified by the apparent inconsistency of their range relative to the observed oblique modes. The off-path (forward scatter) signals were identified by converting the vertical ionograms to oblique ones, paying careful attention to the MUF and "cutoff" frequencies relative to the angles and geometry of the path.

A number of examples of "M" and "N" type of modes were also identified by similar techniques. In a few examples uncertainty existed because of unusual ionospheric conditions or insufficient data, particularly mid-path soundings.

The data processed for the DAASM maps and coherence was taken simultaneously on any two of nine available test frequencies. The operator constantly monitored an "A" scope presentation, and manually adjusted two sets of range-gates on each frequency, selecting the most significant echo or echoes depending on the conditions being investigated. The delays of these gates were carefully logged throughout the flights together with other information and comments regarding the character of the observed echoes.

It was found that when the range gates at both frequencies were set to the same range, the echo was usually some type of an E-mode, that is, there was very little change in delay with frequency as would be expected for an E-mode, (Table 1). In other cases, the range-gate differences were carefully plotted on overlays and matched to both the measured and constructed oblique ionograms. The spread of each set of range-gates throughout most of the flights was set to sample four ranges separated by 80 μ sec each, or an overall range-gate spread of 76 km (one way). Each set of range gates consists of four gates, the separation of which is variable in steps of 40 μ sec. The absolute value of the total range cannot be determined due to the necessity of periodically "drifting" the pulse echoes back into the digitizers range as the aircraft moves further or closer in range. However, the information on the changes of range made between "drifts", as well as the difference in range between the test frequencies was used. Since the data for the "maps" can be processed for each gate individually, the range separation between map is 18 km. Some of the samples below are the result of the sequence of the shifting of gates

from one mode to another as the mode situation changes during a period of a few minutes, for example, Flight 4-193, between 1940 and 1943. Table 1 presents a summary of the mode(s) lying in the range gates at each of the two test frequencies for each of the selected samples.

Table 1. Summary of Mode Identifications

Flight	Time UT	DAASM Frequency No. 1		DAASM Frequency No. 2		Dist. km
		MHz	Mode	MHz	Mode	
4-058	2325	8.22	E _{an}	10.22	None	1710
	2343	8.22	F ₂	11.22	E _{an}	1960
	0058	8.22	E _a	6.62	E _a	1830
4-060	0303	13.22	E _a	11.22	E _a	1900
	0348	13.22	None*	11.22	E _a *	2480
	0610	13.22	*	11.22		1590
	0710	13.22	None	11.22	None	930
4-141	2325	8.22	E _S	6.62	E _S	910
	2332	8.22	E _S	6.62	E _S	810
4-142	2153	8.22	E _a ¹	6.62	E _a ¹	680
	2253	13.22	E _S	11.22	E _S	1440
	2342	13.22	E _S ²	11.22	E _a	2070
	2355	8.22	E _S ³	11.22	E _a	2270
	0238	8.22	E _S	11.22	E _S	1630
	0251	8.22	E _S	6.62	E _S	1460
	0305	8.22	E _S	6.62	E _S	1320
	0336	8.22	E _S	6.62	E _S	920
4-193	1655	8.22	E	11.22	E	1380
	1718	13.22	No sig	11.22	E _S ¹	1680
	1721	8.20	No sig	11.22	E _S ¹	1721
	1920	8.22	F ₁ ^l or E _a	6.62	F ₁ ^l	1440
	1940	8.22	F ₁ ^l + E _h	6.62	F ₁ ^l + F ₁ ^h	1167
	1941	8.22	F ₂ ^h	6.62	F ₂ ^l (+F ₁ ^h)	1153
	1943	8.22	F ₂ ^l	6.62	F ₁	1127
4-196	1641	8.22	F ₂	11.22	E or E _S	1260
	1940:15	8.22	M(2F ₂ , 1E)	11.22	F ₁ (or F ₂)	1952
	1940:45	8.22	M(2F ₂ , 1E)	11.22	E or E _S	1952
	1941	8.22	M(2F ₂ , 1E)	11.22	E or E _S	1940
	1942	8.22	M(2F ₂ , 1E)	11.22	E or E _S	1928
	2038	8.22	F ₁ ^h	6.62	F ₂ ^l	1250
	2100	6.62	E	8.22	E _S	966
	2130	6.62	E _S	8.22	E	610

* Ionograms not available

1. with spreading
2. with backscatter present in DAASM
3. off path

Symbols: E_a = Arctic (E)
E_{an} = Arctic night (E)
E_S = Sporadic (E)

Subscript l = low ray
Subscript h = high ray
M(2F₂, 1E) = M type, 2 hop F₂,
one hop E.

3. ARRIVAL ANGLE MEASUREMENTS

The technique for generating the DAASM maps is fully discussed in Reference 1. Here we have examined the character of the received aircraft transmissions in terms of the angular deviation and angular spreading of the source. The aircraft transmitter is essentially a point source located at ranges varying from 900 to 2800 km from the Goose Bay, Labrador, receiving site. For all of the measurements described in this report, the aircraft bearing from Goose Bay varied between 000°T and 328°T , that is, primarily to the north of Goose Bay. The six DAASM missions, two in February 1974, two in May 1974, and two in July 1974 were concentrated in the afternoon through midnight time period. The details of the flight paths are given in Reference 1 and the propagation paths relative to the oval are shown in Figures 1 to 6.

Most of the data processed used the intermediate-sized array with an aperture of 720 m and with an average half power beam width of 2.5° . Accurate logs were kept by the aircraft navigators and with the system beamwidth a 3° accuracy is placed on the azimuthal angle measurement. For all the data, Figure 8 shows the measured deviation of the arrival angle of the aircraft signal from the expected position.

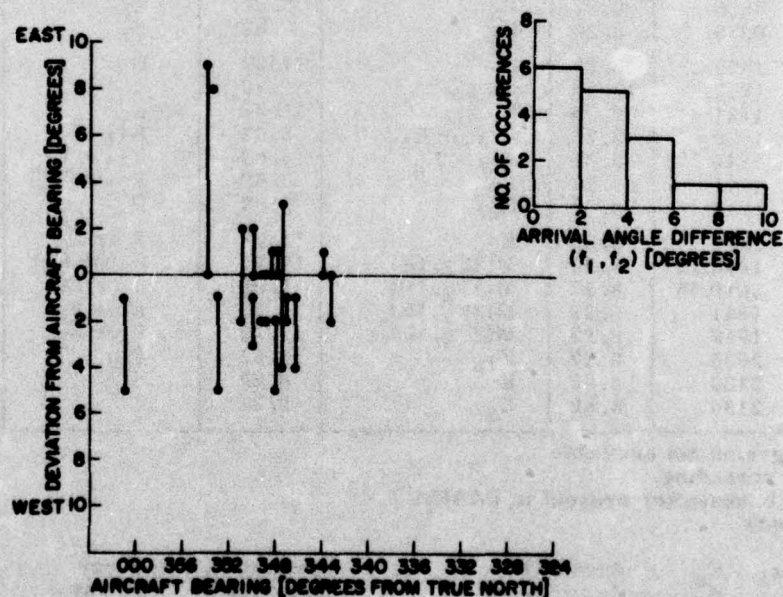


Figure 8. Arrival Angle vs Aircraft Bearing

In analyzing the angular differences between the apparent and true bearing to the aircraft, special consideration was given to Flight 142. In general, the apparent direction of the aircraft was determined from the DAASM map by locating the largest signal, on the assumption that the strongest signal recorded was that of the aircraft. Except for Flight 142 this technique has worked well with little or no ambiguity. In the twelve observations reported on for Flight 142, the nine largest deviations were observed using this rule. The deviations varied from 6° to 13° East of the true A/C position. In seven of these nine measurements there was a second signal peak, smaller by less than 3 dB, closer to the true position of the aircraft. An example of this is shown in Figure 9. For the 8.2 MHz frequency, the point source aircraft signal has arrived at the receiver as a very complex signal with peaks at several Doppler frequencies and arrival angles. In this case, as in seven other maps for this flight, there are several modes in addition to a great-circle mode. Only the great-circle modes were counted in determining the distribution of angular deviation in Figure 10. Summarizing the results; for 67 percent of the cases, the angular deviation was less than or equal to 3°. This is well within the uncertainty in the measurement caused by beamwidth and navigator error. For those remaining cases where the angular spreading was not so severe as to make the deviation measurement difficult, the deviation did range out to 9° from the true aircraft bearing.

Positive and negative deviations occurred with almost equal frequency. It is interesting to note that if the data are divided into two groups; one prior to 2200 UT and one later, 83 percent of the deviations were to the West of the true position before 2200 UT and 82 percent were to the East after 2200 UT. The large bulk of the data represents E-layer propagation. Higher critical frequencies lie to the West of the midpoint in the afternoon (before 2200 UT) as a result of the effects of solar control. This increasing gradient to the West, increasing from 2.5 MHz at the midpoint of the aircraft/Goose Bay path to 3.0 MHz some 700 km West, will tend to make the arrival angle deviate to the West of the true path (Figure 11). After 2200 UT, it may be possible that the approaching auroral oval with a median nighttime arctic high critical frequency, $f_o E_a$, of 2-3 MHz⁴ turns the gradient around and makes deviations to the East more likely. In fact the largest observed easterly deviations have been identified with auroral E-layer reflections.

The pairs of points joined by a connecting line in Figure 8 indicate the deviations of the two frequencies simultaneously measured. For 65 percent of these pairs, the arrival angle difference was less than 4°.

In summary, the angular deviations associated with E-modes are in general small though deviations as large as 9° did occur.

4. Gassmann, G. T. (1971) On Modelling the Arctic Ionosphere, Summary paper presented at AGARD Technical Meeting in Lindau/Harz, Germany.

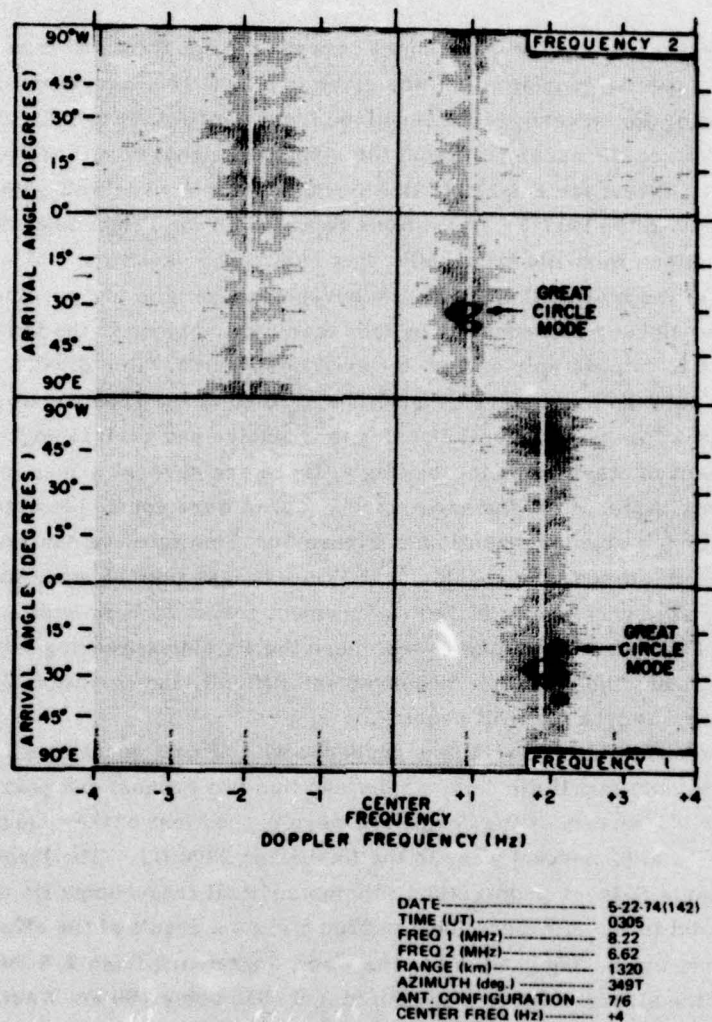


Figure 9. DAASM Map Flight 4-142

From the same predominantly E-mode data, the width of the angular spectrum was determined. The distribution of the width of the angular spectrum at 3 dB down from the peaks is shown in Figure 12. The median angular width is 4° with a range from 2 to 6°. From this distribution, 41 percent of the observations were spread 3° or less.

From the small amount of F-mode data, there is a slight tendency to greater spreading with a median value of 5°.

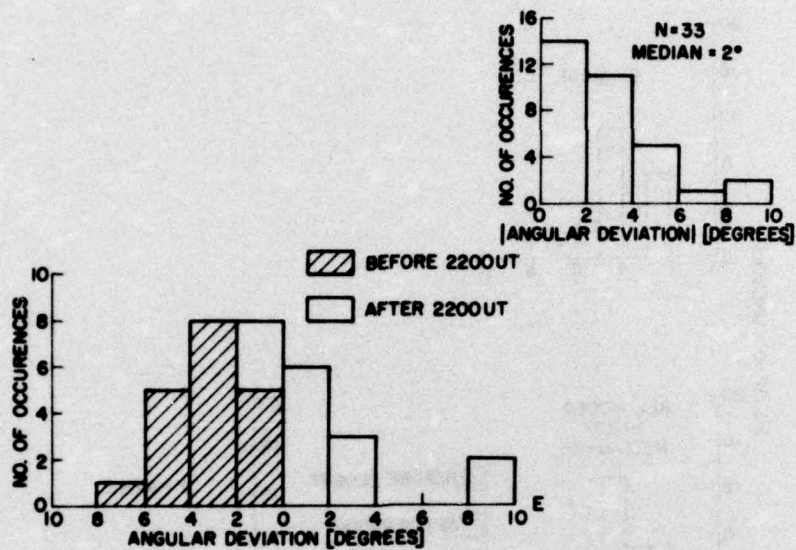


Figure 10. Distribution of Angular Deviations

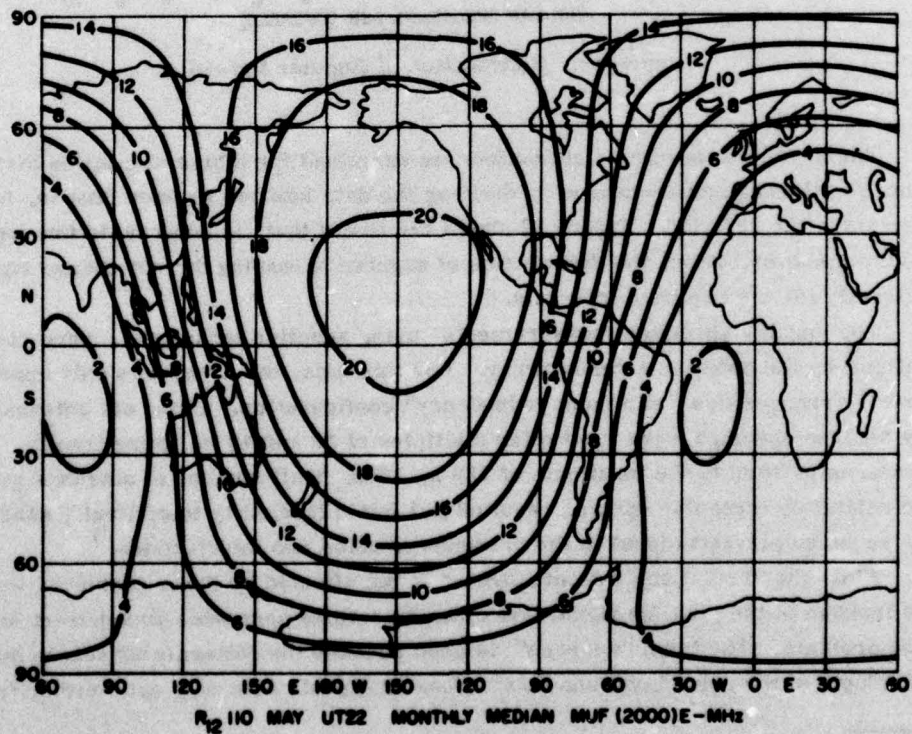


Figure 11. f_oE Contours

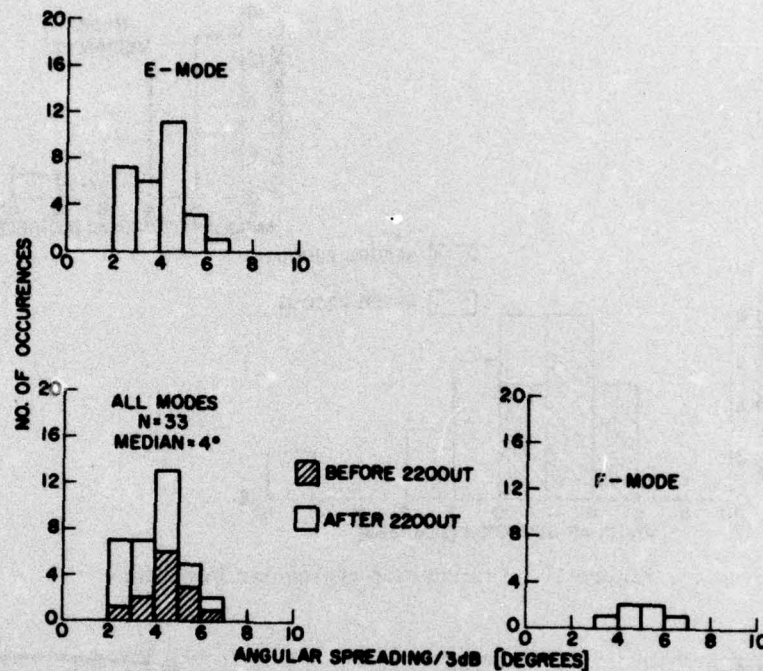


Figure 12. Distribution of Angular Spread

The angular spreading distribution was examined for a bias similar to that found for the angular deviations by dividing the data into two groups, that is, before and after 2200 UT. Figure 12 shows the result that, in contrast to the angular deviations distribution, the distribution of angular spreading did not change significantly for the two time intervals.

The angular spectrum measurements, using adaptive techniques, were made difficult by the selected antenna array. For this data, the array was only approximately arranged in a "minimum redundancy" configuration. Using six antennas the derived spacings were most often multiples of 30 and 40 m, going from a minimum of 30 m to the maximum of 720 m. The small number of antennas and the relatively irregular spacing resulted in limited flexibility to optimally handle the received aircraft signal in the presence of noise and interference.⁵

While the arrival angle determination is not affected by these considerations, the leakage of the aircraft signal into other directions generates an apparent side-lobe problem. The term "apparent" is used because the pattern is not deterministic but adapts to the noise level and other coherent signals than may exist either from

5. Varad, R. and McComish, W. C. (1975) The Maximum Likelihood Method/ Applications to DAASM Studies, Boston College, AFCRL-TR-75-0551.

additional propagation modes from the aircraft or interferers. The actual mean sidelobe level achieved depends, in a complicated fashion, on signal-to-noise ratio and the location of other sources.

The relatively large amplitudes that occur at all angles at the Doppler frequency of the aircraft signal can be seen on all the DAASM maps in Reference 1.

The small number of degrees of freedom associated with antenna array prevent the "maximum likelihood" adaptive method from effectively cancelling the aircraft signal and at the same time minimizing the ambient noise when the array is steered to a direction other than the bearing of the aircraft signal. Two examples of angular spectra are shown in Figure 13. These patterns were obtained with only six antennas and approximately 10 dB signal-to-noise ratio. The lobed structure makes the identification of multimode propagation difficult. This problem can be eased by increasing the number of antennas.

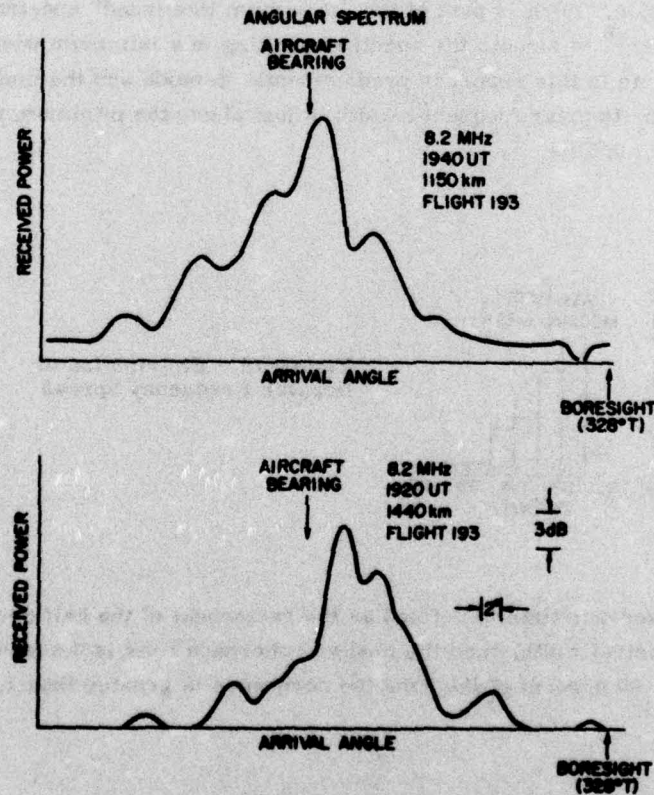


Figure 13. Antenna Pattern

4. DOPPLER FREQUENCY MEASUREMENTS

In this part of the study, the effects of the propagation medium on the transmission frequency from the aircraft are examined. Because of the aircraft velocity a Doppler frequency is added to or subtracted from the transmitter frequency. Systematic and random motions in the ionosphere will also affect the received frequency. Unfortunately, absolute Doppler frequencies could not be measured because of the inability to synchronize the two oscillators at the aircraft and Goose Bay ground site to the same frequency. This uncertainty in the frequency offset does not affect the measurement of Doppler frequency spreading; that is, the degree to which the received signal no longer contains a single frequency but is spread in the frequency domain as the wave passes through the irregular ionosphere. Figure 14 shows the distribution of Doppler frequency spectral width (3 dB) of the received signal. In order to accomplish the cross-spectral matrix inversion, which is part of the "maximum likelihood" spectral estimation, it was necessary⁶ to smooth the spectra resulting in a minimum width of 0.3 Hz. The data sample in this report is predominantly E-mode and the median value of 0.33 Hz for the Doppler frequency width is just above the minimum width. The upper decile is 0.6 Hz.

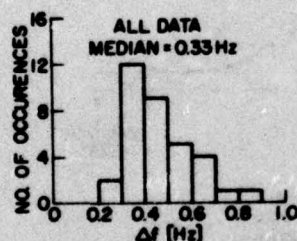


Figure 14. Distribution of Doppler Frequency Spread

If the coherence time is defined as the reciprocal of the half power Doppler frequency spectral width, then the median coherence time is 3 seconds. From the upper decile, 90 percent of the time the coherence is greater than 1.67 sec for the E-mode.

6. Pfister, W., Sales, G. and Varad, R. (1975) Pulse Sounding With Closely Spaced Receivers as a Tool for Measuring Atmospheric Motions and Fine Structure in the Ionosphere. VII Data Processing with Different Techniques for Cross-Power Spectra, AFCRL-TR-75-0194.

5. CONCLUSIONS

The larger fraction of the data used in the DAASM analysis represents E-mode propagation. E-modes were selected because, first, they were often the only propagation mode and second, when there were other modes the E-mode was often the strongest and therefore had been selected by the operator for recording.

This selection process had resulted in a set of data which may represent the best conditions for auroral zone propagation. Under these "best" conditions there is considerable perturbations to the wave character compared to what might be expected for a similar mid-latitude path. The deviations and spreading of the signal characteristics would pose a serious problem for an OTH-B radar correlation/identification process. However, in regions, particularly to the north, where aircraft traffic is normally low, larger errors in the correlation process can be tolerated.

The small quantity of F-mode data indicates a more severe perturbation of the radio wave characteristics.

Severe multipath data correlates well with propagation across the night oval. Approximately 80 percent of these cases correspond to oval reflections. Some examples of multimode propagation from three flights can be seen on pages 66, 78 and 90 of Reference 1. The severity of this problem is exaggerated by the proximity of the DAASM receiving site to the oval. A more removed site would not likely suffer such large angular deviations due to multiple auroral reflection.

References

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3. Kift, F. (1960) The propagation of HF radio waves to long distances, Inst. of Elec. Engrs., Paper No. 3156E.
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